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Possibility of the LBL experiment with the high intensity proton accelerator ⋆

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Abstract

We study physics possibility of Very Long Base-Line (VLBL) Neutrino-Oscillation Experiments with the High Intensity Proton Accelerator, which will be completed by the year 2007 in Tokai-village, Japan. As a target, a 100 kton-level water-Čerenkov detector is considered at 2,100 km away. Assuming the pulsed narrow-band ν_μ beams, we study sensitivity of such experiments to the neutrino mass hierarchy, the mass-squared differences, one CP phase and three angles of the lepton-flavor-mixing matrix. We find that experiments at a distance 2,100 km can determine the neutrino mass hierarchy if the mixing matrix element $|U_{e3}|$ is not too small. The CP phase and $|U_{e3}|$ can be constrained if the large-mixing-angle solution of the solar-neutrino deficit is realized.

In order to measure the neutrino oscillation parameters, such as the neutrino mass-squared differences and the elements of the 3×3 Maki-Nakagawa-Sakata (MNS) lepton flavor-mixing matrix elements [2], various long base-line (LBL) neutrino oscillation experiments are proposed. In Japan, as a sequel to the K2K experiment, a new LBL neutrino oscillation experiment between the High Intensity Proton Accelerator (HIPA) [3] and the Super-Kamiokande (SK) with the base-line length of L=295 km has been proposed [4]. In this talk, I discuss the physics potential of Very Long Base-Line (VLBL) neutrino oscillation experiments with HIPA and a huge neutrino detector [5] in Beijing, at about L=2,100 km away. As a beam option, the pulsed narrow-band ν_μ beam (NBB) is assumed. For a target at L=2,100 km, we consider a 100 kton water-Čerenkov detector which is capable of measuring the both ν_μ-like and ν_e-like events. We study the sensitivity of such experiments to the neutrino

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mass hierarchy, the mass-squared differences, the three angles and one CP phase of the MNS matrix [1].

In general, the MNS matrix has three mixing angles and three phases. Two Majorana phases do not contribute to the neutrino oscillation. Without losing generality, we can take U_{e2} and $U_{\mu 3}$ to be real and non-negative. By allowing U_{e3} to have the complex phase $U_{e3} = |U_{e3}|e^{-i\delta_{\rm MNS}}$ $(0 \leq \delta_{\rm MNS} < 2\pi)$, the four independent parameters are $U_{e2}, U_{\mu 3}, |U_{e3}|$ and $\delta_{\rm MNS}$. The constraints on the MNS matrix and the mass-squared differences are given by the atmospheric-neutrino[6], solar-neutrino[7] and the CHOOZ reactor experiments[8]. An analysis of the atmospheric-neutrino data from the SK experiment [6] finds $\sin^2 2\theta_{\rm ATM} \sim (0.88-1.0)$ and $\delta m^2_{\rm ATM}({\rm eV}^2) \sim (1.6-4.0)\times 10^{-3}$. From the observations of the solar-neutrino deficit by the SK collaboration [7], the MSW large-mixing-angle solution (LMA) is preferred to the others. The CHOOZ experiment [8] gives the constraint $\sin^2 2\theta_{\rm CHOOZ} < 0.1$ for $\delta m^2_{\rm CHOOZ} > 1.0\times 10^{-3}\,{\rm eV}^2$. From these experiments, the independent parameters in the MNS matrix are obtained as

$$U_{\mu 3} = \sqrt{1-\sqrt{1-\sin^2 2\theta_{\rm ATM}}}\Big/\sqrt{2}\,, \tag{1}$$

$$U_{e2} = \sqrt{1-|U_{e3}|^2-\sqrt{(1-|U_{e3}|^2)^2-\sin^2 2\theta_{\rm SOL}}}\Big/\sqrt{2}\,, \tag{2}$$

$$|U_{e3}| = \sqrt{1-\sqrt{1-\sin^2 2\theta_{\rm CHOOZ}}}\Big/\sqrt{2}\,. \tag{3}$$

All the other matrix elements are then determined by the unitary conditions. Hereafter, we have made the identification $\delta m^2_{\rm SOL} = |\delta m^2_{12}| \ll |\delta m^2_{13}| = \delta m^2_{\rm ATM}$, with $\delta m^2_{ij} = m^2_j - m^2_i$.

Since all the above constraints are obtained from the survival probabilities which are even-functions of δm^2_{ij}, there are four neutrino-mass hierarchy cases corresponding to the sign of the δm^2_{ij} as shown in Fig. 1. If the MSW effect is relevant for the solar-neutrino oscillation, then the hierarchy cases II and IV are not favored. The hierarchy I (III) is called 'normal' ('inverted') hierarchy, which corresponds to $\delta m^2_{12} > 0$ and $\delta m^2_{13} > 0$ ($\delta m^2_{13} < 0$).

In order to examine the capability of the VLBL experiments in determining the parameters, we use the χ^2 which is a function of the three angles, the two mass-squared differences, the CP phase, the flux normalization factors and the matter density. The event number for the χ^2 are derived from combining two experiments with different base-line length, $L = 2,100$ km (HIPA-to-Beijing) and $L = 295$ km (HIPA-to-SK). For a VLBL experiment at $L = 2,100$ km, we assume the statistical significance of 500 kton·year each with two NBB whose peak energy is 4GeV and 6GeV respectively. As for the LBL experiment at L= 295 km, we assume that 100 kton·year for the low-energy NBB with $\langle p_\pi \rangle$=

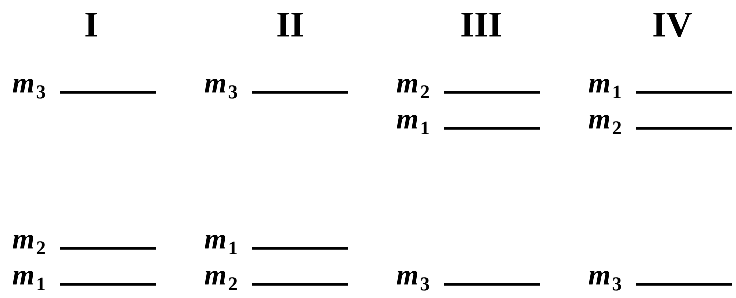

Fig. 1. Schematical view of the four cases of neutrino-mass hierarchy.

2 GeV (NBB(2π)). The data obtained from the LBL experiment is what SK can gather in approximately 5 years with 10^{21} POT par year.

Thanks to the enhancement of matter effect, it is expected to distinguish the neutrino-mass hierarchy cases in such VLBL experiments. We can determine the neutrino mass hierarchy at 3σ level if $\sin^2 2\theta_{\text{CHOOZ}}$ >0.04 by using this combination. Also it is found that, if the LMA scenario is realized in Nature, $\sin^2 2\theta_{\text{CHOOZ}}$ and δ_{MNS} can be constrained at 1σ level in favorable cases. If the LMA scenario is realized in Nature and $\sin^2 2\theta_{\text{CHOOZ}} \gtrsim 0.06$, the SMA/LOW/VO scenarios can be rejected at 1σ level when δ_{MNS} is around $0°$ or $180°$ but not at all when δ_{MNS} is around $90°$ or $270°$. For the atmospheric-neutrino oscillation parameters, $\sin^2 2\theta_{\text{ATM}}$ is measured to 1% level and δm^2_{ATM} with the 3% accuracy when $\sin^2 2\theta_{\text{ATM}} = 1.0$, $\delta m^2_{\text{ATM}} = 3.5 \times 10^{-3}$ and the LMA scenario are realized in Nature.

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